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Coastal urban reliance on groundwater during drought cycles: Opportunities, threats and state of knowledge

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Review

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Abstract

Urbanisation and population growth are concentrated on the coast with approximately 40% of the human population living within 100 km of the ocean. The freshwater systems on which coastal urban areas rely are vulnerable to bidirectional pressures including coastal processes such as sea-level rise and coastal erosion coupled with land use changes and pollution occurring in inland catchment areas. These threats are likely to be amplified in the future under climate change conditions and more frequent and severe drought periods are expected to jeopardise already constrained water supply systems. Groundwater is used as a freshwater resource globally and is especially important as a conjunctive supply during drought periods due to perceived buffer capabilities. However, several threats impact coastal aquifers due to over-abstraction, such as salinisation, land subsidence and groundwater flooding and often these subterranean resources are “out of sight and out of mind” when it comes to management strategies. Here, we present an assessment of current issues and management options relevant to coastal aquifers using recent literature. These insights provide knowledge on global issues relevant to groundwater resources, especially regarding water use during droughts. This is exemplified using a South African case study of two metropolitan municipalities that have experienced or are experiencing severe multi-year droughts. Both municipalities have grappled with the depletion of surface water resources, which constitutes the bulk of the local water supply systems. Consequently, groundwater resources have been explored as an augmentation strategy. Although groundwater resources may be useful in alleviating drought effects, it is crucial that a local understanding of the aquifers is developed through baseline hydrological studies and long-term monitoring. Furthermore, unregistered groundwater use needs to be quantified. Finally, a holistic groundwater management view, and the communication thereof, is required to ensure the sustainable management of coastal aquifers.

Impact statement

This study provides an overview of recent literature related to groundwater use in coastal urban areas, especially as an emergency resource during drought periods. The primary threats to coastal aquifers in the past, present and future are highlighted, as well as potential sustainable management solutions. A global comparison of risks and possible solutions regarding coastal aquifer management is imperative given increasing pressures on these systems related to socio-economic development, population growth and climate change. This is especially important in the context of droughts as these events affect both the quantity and quality of water available to densely populated coastal urban areas, which are vulnerable to resource degradation from both catchment and marine processes. Droughts coupled with groundwater abstraction also increase saltwater intrusion in aquifers with marine connectivity. As an area susceptible to severe droughts, a South African case study is used to illustrate the historical reliance of two coastal metropolitan municipalities on surface water resources and how groundwater abstraction has been used to supplement diminishing water supply. To our knowledge, this is the first study to review the literature available on the water crises experienced by both coastal municipalities. This assessment reveals priority management principles linked to sustainable water resource use during drought disasters in the coastal zone.

Introduction

Sustainable and reliable potable freshwater supply has been a limiting feature for human occupation of landscapes historically, especially at the coast (Rishworth et al., 2020a; Rosinger, 2021), and will restrict emergent economic development in the future in all regions (Garrick et al., 2017). Behavioural changes surrounding how water use is minimised across all sectors, how its lifecycle is optimised to restrict wastage and how alternative water supplies are utilised present solutions to managing water scarcity. The latter of which includes sources such as groundwater which have been used for millennia as dependable freshwater sources but are not always well-understood locally in terms of hydrological cycling.

Many groundwater reserves have been unsustainably managed and are at risk of depletion globally (Famiglietti and Ferguson, 2021; Jasechko and Perrone, 2021), although in other areas, such as Sub-Saharan Africa, groundwater resources are generally underdeveloped (Cobbing, 2020). Coastal aquifers (groundwater resources situated along the coast and linked to or influenced by coastal or marine ecosystems) face additional threats driven by climate change and urbanisation compared to their inland counterparts (e.g., Boretti and Rosa, 2019). These include sea-level rise (SLR), reduced recharge, storm surges (including hurricanes and cyclones), coastal flooding and erosion (Ferguson and Gleeson, 2012; Barbier, 2015; Erostate et al., 2020; Chesnaux et al., 2021). Coastal urbanisation is more concentrated compared to inland, and this is exacerbated by the increasing trend of coastal tourism, migration and population growth to coastal areas (Neumann et al., 2015; Parisi et al., 2018). As a result, increased anthropogenic pressures at the coast may accelerate pollution, over-abstraction and compaction of coastal aquifers causing water quality degradation, seawater intrusion and land subsidence (e.g., Ferguson and Gleeson, 2012; Chang et al., 2019; Han and Currell, 2022). Thus, the urbanisation of continental coastlines and islands coupled with increasing threats of climate change, coastal vulnerability and associated extreme events such as droughts adds pressure to an already constrained system of freshwater supply (Boretti and Rosa, 2019; see Figure 1). Therefore management and supply of alternative resources such as groundwater are becoming more crucial under these circumstances along coastlines.

Droughts may be classified according to their origin (e.g., meteorological drought) or effect (e.g., agricultural, hydrological). A prolonged meteorological drought, which is caused by below-average precipitation for a given time, may develop into an agricultural or hydrological drought. An agricultural drought is characterised by deficits in soil moisture and often has negative effects on crop yields. On the other hand, a hydrological drought can be sub-categorised (e.g., groundwater drought) and refers to reductions in water levels and reservoir storage (e.g., Schreiner-McGraw and Ajami, 2021). In this assessment, "drought" generally refers to a persistent meteorological drought, which has manifested as a hydrological drought.

This study evaluates and reviews recent literature discussing the drivers, pressures, states and impacts influencing coastal aquifer functioning and potential management responses, especially in a drought context.

Perspective

Groundwater use and risks in the coastal zone

As surface water resources become more limited and progressively degraded, coastal groundwater abstraction has increased markedly and is expected to increase even further under predicted drier conditions in the future with more frequent, long-lasting and intense droughts anticipated (e.g., Parisi et al., 2018; Erostate et al., 2020).

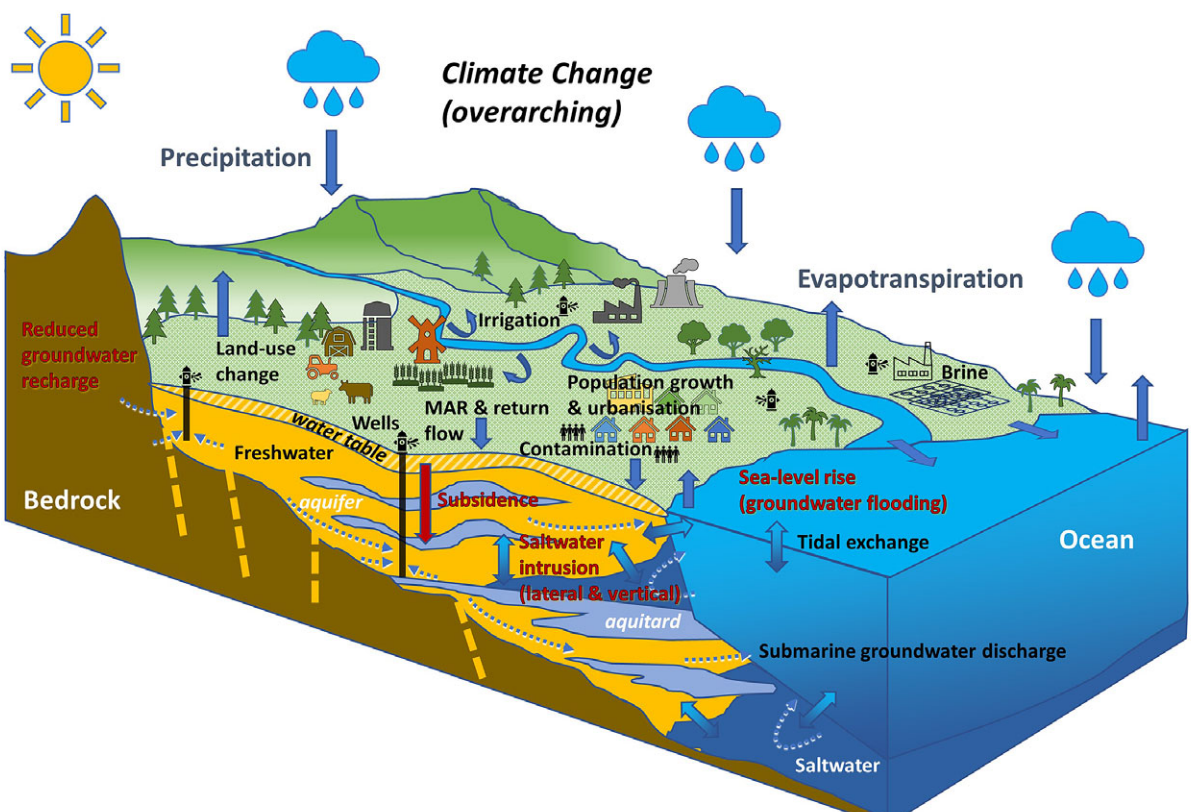

Figure 1. Schematic portraying the issues, opportunities and dynamics related to ground water and its management at the coast in light of future climate change, sustainable development and drought threats. This demonstrates key issues relevant to coastal urban reliance on groundwater. Based on and adapted from graphical abstract of Han and Currell (2022).

These climatic changes (higher temperatures, evapotranspiration and decreased precipitation) will further affect groundwater resources through decreased recharge (e.g., Stigter et al., 2014; Unsal et al., 2014). The consequent impacts of declines in precipitation and groundwater recharge are expected to be especially pronounced in arid and semi-arid regions and coastal regions, such as small islands, that rely exclusively on rainwater harvesting (RWH) and groundwater resources for water supply (e.g., Stigter et al., 2014; Unsal et al., 2014; Kopsiaftis et al., 2017). Urbanisation may further decrease groundwater recharge by the replacement of natural permeable landscapes with hard, impermeable surfaces such as roads. These urban surfaces linearly direct surface runoff to lentic waterways more effectively and therefore reduce infiltration opportunities (Han et al., 2017; Lorenzo-Lacruz et al., 2017; Minnig et al., 2018; Frommen et al., 2021). As such, this will contribute to the coastal squeeze of coastal urban aquifers since these systems are wedged between developed urban areas and rising seas (Vitousek et al., 2017).

Coastal threats and changes (e.g., SLR, storm surges, coastal erosion and land subsidence) may occur simultaneously and/or have knock-on effects leading to the occurrence or acceleration of other pressures, usually intensified through urbanisation and development. The onset of coastal pressures may, however, also be triggered inland such as in the case of coastal erosion caused by dam construction and the resultant changes in sediment source and coastal sediment dynamics (e.g., Huang and Jin, 2018 and references therein; Hzami et al., 2021). Coastal erosion may accelerate land losses beyond those caused by SLR, or erosion may amplify the effects of SLR, causing groundwater salinisation and reductions in groundwater recharge (Baharuddin et al., 2018; Chesnaux et al., 2021). This is of further concern since the decrease in groundwater recharge may be a more important issue than SLR in flat low-lying coastal areas (Parisi et al., 2018). Diminished groundwater discharge levels due to declines in groundwater levels, whether induced by abstraction or reductions in recharge, affect the rest of the hydrologic system through decreased river baseflows, lake and spring levels and ultimately result in landscape desiccation (de Graaf et al., 2019). Furthermore, seaward erosion during storm surges of coastal barriers (e.g., dunes), could result in breaching events that may subsequently affect coastal aquifers kilometres inland through vertical saltwater infiltration, with the delayed recovery of the aquifers to a freshwater state lasting longer than the storm event (Giambastiani et al., 2017; Elsayed et al., 2018).

Many coastal hazards, whether caused by anthropogenic or climatic drivers, ultimately lead to coastal inundation (permanent) or flooding (temporary) (*sensu* Flick et al., 2012) (hereafter collectively referred to as submergence). Three types may be recognised, namely: 1) marine submergence (surface submergence with marine water through, e.g., tidal flooding, SLR, storm drain backflow); 2) groundwater submergence (rise in groundwater levels as groundwater is displaced in response to, e.g., SLR or wastewater network leaks) and 3) precipitation-driven submergence (through large rainfall events) (Han et al., 2017; Minnig et al., 2018; Habel et al., 2020; Rahimi et al., 2020; Su et al., 2020; Frommen et al., 2021). Furthermore, these submergence types may compound each other, which can result in "snowballing" impacts compared to isolated occurrences (Habel et al., 2020; Rahimi et al., 2020). For example, modelled scenarios of the Oakland Flatlands, a low-lying coastal area of California, USA indicate that SLR alone will not pose significant threats to urban infrastructure, but coupled with groundwater submergence more than 310 ha will be negatively affected (Rahimi et al., 2020). Excluding the damage to coastal infrastructure and threats to human life, submergence is usually accompanied by groundwater salinisation through seawater intrusion and pollution of aquifers (Habel et al., 2020; Rakib et al., 2020), which exacerbates the degradation of aquifers already under pressure from over-abstraction and droughts by decreasing potability (e.g., in California, USA – Rahimi et al., 2020).

Despite being identified as a hazard to drinking water supply systems more than a century ago (Michael et al., 2017), seawater intrusion and resultant groundwater salinisation are still the primary threat related to coastal groundwater abstraction (Chang et al., 2019). The source of salinity, however, may be natural (seawater trapped in pores from earlier sea level transgressions and dissolution of evaporite minerals, e.g., halite and gypsum) or anthropogenic (related to over-extraction and agricultural return flow) (Nogueira et al., 2019).

Seawater intrusion triggered by over-abstraction from coastal aquifers can result in both landward (lateral) and vertical (upconing) intrusion (Parisi et al., 2018). Coastal aquifers are increasingly at risk from bidirectional contamination as shorelines migrate landward with SLR and seawater intrusion and with pollution pressure from land sources – especially agricultural and industrial (Michael et al., 2017; summarised in Figures 1 and 2). Not only does this leave groundwater resource unsuitable for human use but may also have dire effects on coastal groundwater-dependent ecosystems (GDEs) such as estuaries, lagoons, microbialite ecosystems and coral reefs (Michael et al., 2017; Erostate et al., 2020; Rishworth et al., 2020b). These GDEs are also at risk of state changes or even localised extinction as groundwater levels are reduced or depleted and surface-groundwater connections are disturbed. This is especially relevant in arid or semi-arid coastal regions with a Mediterranean climate, such as those of the Mediterranean basin and the south-western coasts of Australia, Chile, California (USA) and South Africa (Erostate et al., 2020). For example, salinity increases in the microbialite-bearing Lake Clifton, Western Australia has been observed since the 1990s. This is attributed to hydrological changes driven by increased evaporation and decreased freshwater recharge to Lake Clifton due to lower rainfall, groundwater abstraction in the catchment areas and the construction of the Dawesville Channel (Forbes and Vogwill, 2016; Warden et al., 2019). The higher salinity, in addition to higher nutrient loads, is thought to have contributed to a change in the microbial communities of the Lake, although this does not necessarily translate to unfavourable conditions for microbialite formation (Gleeson et al., 2016; Warden et al., 2019). The effects of coastal water crises associated with groundwater salinisation globally may be summarised as conflict of uses between different water users, wetland degradation, loss of crops, soil salinisation, aridity, desertification and health issues (Parisi et al., 2018).

Furthermore, an emerging issue related to coastal groundwater use is that of land subsidence and increased rates of relative SLR. Natural land subsidence of unconsolidated coastal sediments may be accelerated by groundwater abstraction and urban development (see below) and when combined with SLR and storm surges increase the risk of seawater intrusion into aquifers (Huang and Jin, 2018; Shirzaei et al., 2021). This will likely be exacerbated by drought conditions and climate change. For example, model predictions underestimated land subsidence in Yuanchang, Taiwan for the 2011–2012 period due to increased groundwater pumping and reduced recharge during a dry spell (Shirzaei et al., 2021). Relative SLR may pose a further risk to coastal communities through groundwater flooding as unconfined coastal aquifer levels will increase in response to sea level changes. It is anticipated that water tables will either rise the same amount as sea levels, where the additional groundwater can be accommodated, or that the seawater intrusion will displace fresh groundwater, which will discharge through original or new drainage systems (Befus et al., 2020). For instance, coastal cities in Indonesia such as Semarang and the Indonesian capital, Jakarta, are already experiencing the impacts of land subsidence, coastal flooding during high tides and seawater intrusion into aquifers (Abidin et al., 2015). This is partly due to the demand for clean water outstripping surface water supply and consequently the over-abstraction of groundwater to make up the water supply deficit. Furthermore, urban development results in the consolidation of sediments, increased surface runoff and decreased groundwater recharge during rain events (Abidin et al., 2015; Pramono, 2021; Taftazani et al., 2022). As a result, more than 80% of groundwater samples from monitoring wells in northern Jakarta's groundwater basins exceed the recommended limits of salinity for human consumption (Taftazani et al., 2022) and aquifers of entire small islands are brackish or saline during dry seasons (Cahyadi, 2018).

Water quality degradation through anthropogenic and geogenic pollution linked to increased water demand will further decrease both surface and groundwater resources available for use at the coast (e.g., Han and Currell, 2022). Urban aquifers are often associated with pollution by emerging contaminants (e.g., pharmaceuticals and personal care products) and nutrient loading through aqua- and agricultural activities, septic tanks, cemeteries and landfills (e.g., Lapworth et al., 2017; Boretti and Rosa, 2019; Burri et al., 2019; Preziosi et al., 2019; Han and Currell, 2022). Slow-moving aquifers and groundwater-fed rivers can release persistent organic pollutants, such as anthropogenic per- and polyfluoroalkyl substances (PFAS), into marine environments long after its initial release into the upstream environment (Sunderland et al., 2019; Zhang et al., 2019a; Ruyle et al., 2021). Coastal point sources include airports and ports (Li et al., 2022), while wastewater treatment works, landfills and urban runoff also contribute to the transportation of PFAS (e.g., Hepburn et al., 2019; Cui et al., 2020). The residence time of certain PFAS species may be further lengthened by adsorption driven by tidal and salinity effects in the coastal zone resulting in bioaccumulation in benthic organisms. In fact, seafood is considered the primary human dietary exposure pathway to PFAS compounds (Sunderland et al., 2019; Zhang et al., 2019a). However, PFAS adsorption in coastal sandy aquifers may act as a natural attenuation process (Li et al., 2022). These pathways are therefore not fully understood but present an emerging research priority and likely threat to coastal aquifers.

Management of water crises and groundwater use in the coastal zone

When facing a water scarcity crisis, there are two management strategies that can be employed, namely, supply management (i.e., increase the available resources) and demand management (i.e., decrease water use) (Lam et al., 2016). Although droughts occur naturally as a part of the hydrological cycle, their frequency and intensity are increasing under climate change scenarios. Emergency procedures during droughts often mean that more wells are drilled, which may accelerate aquifer depletion (Petersen-Perlman et al., 2022) and are therefore likely not a sustainable solution (Figure 2). Water supply management in urbanised coastal areas during droughts cannot rely on a "wait 'til it rains'" approach (Parisi et al., 2018). Rather, socio-ecological and collaborative strategic management of water supply is required to effectively manage water resources and prevent aquifer salinisation (Parisi et al., 2018).

Some problems related to drought and groundwater management are caused by governance misalignments (Petersen-Perlman

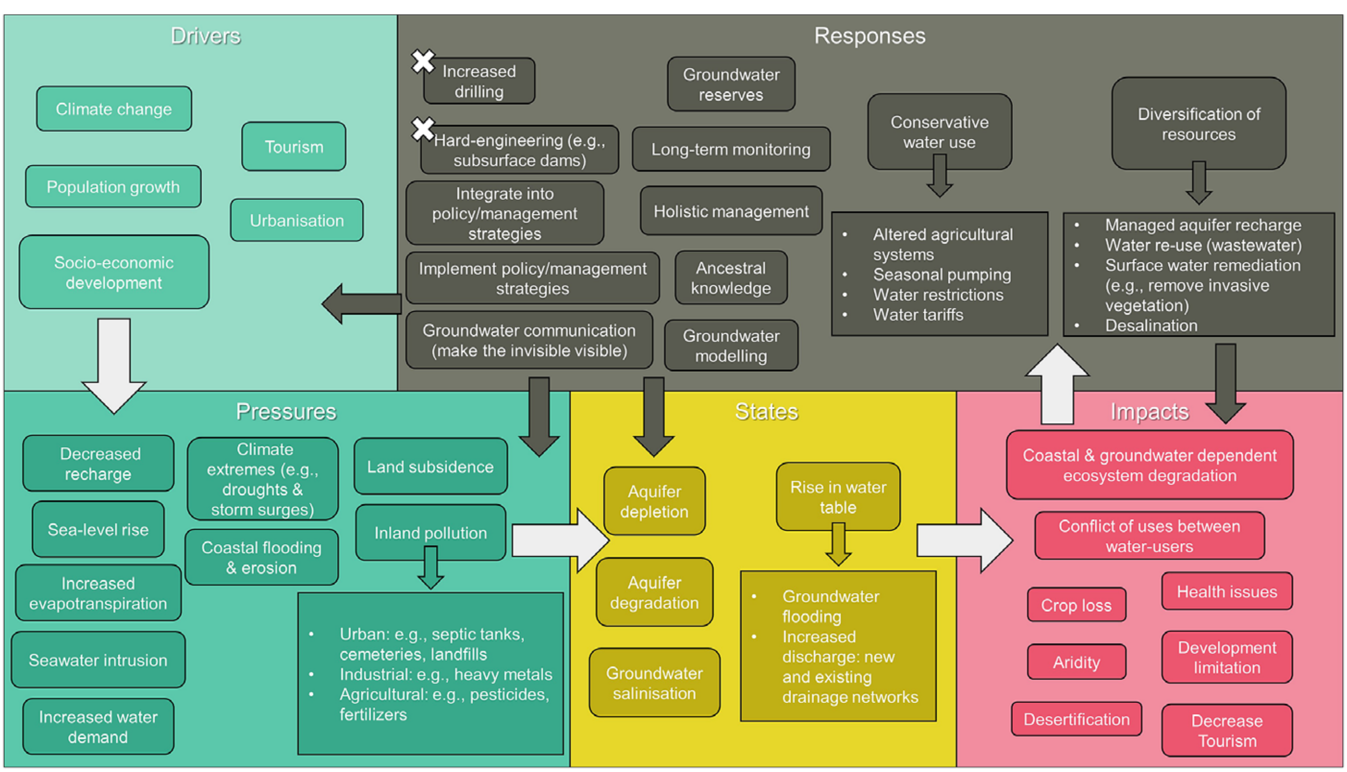

Figure 2. Driver-Pressure-State-Impact-Response (DPSIR) framework regarding groundwater use in coastal urban areas. Responses with a cross indicate there are large negative implications reported with the use thereof.

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et al., 2022). For example, the Salento aquifer in Italy is experiencing groundwater salinisation and despite droughts in the area, salinity effects are not considered in groundwater management practices and no systematic monitoring takes place (Parisi et al., 2018). Furthermore, although the national legislation of selected water-scarce and drought-prone countries protects GDEs (e.g., Australia) or advocates for environmental requirements (e.g., South Africa) (Rohde et al., 2017; Erostate et al., 2020), monitoring of actual regional groundwater abstraction is often lacking or management regulations are not met (Bekesi et al., 2009; Erostate et al., 2020; Kent et al., 2020; Robertson, 2020). That being said, in Australia progress in GDE management has been achieved through comprehensive adaptive management frameworks that are informed by legislation as well as scientific and technological advancements coupled with regional datasets (Rohde et al., 2017).

Other accounts of successful groundwater management strategies and implementation of policy during droughts in coastal urban areas include the employment of managed aquifer recharge (MAR). The main applications of MAR are to increase water storage and provide a water resource more resilient to climate change, while water quality is also often improved by pollutant attenuation during infiltration (e.g., Kazakis, 2018; Dillon et al., 2020). This strategy of MAR is often implemented in regions with seasonal precipitation cycles to mitigate surface-water shortages during the dry months, such as in India (Glendenning and Vervoort, 2011). A small-scale example, stemming from ancestral knowledge, is that of coastal Ecuador using constructed "tapes" or artisanal dikes to increase groundwater storage during periods of water scarcity (Carrión et al., 2018). Furthermore, MAR has been widely applied to prevent seawater intrusion into coastal aquifers by maintaining groundwater levels and driving the saltwater wedge seaward or decreasing aquifer salinisation through blending with lower salinity surface water, such as treated wastewater (e.g., Masciopinto, 2013; Bachtouli and Comte, 2019; Alam et al., 2021). For example, in Jakarta, Indonesia the effects of land subsidence and seawater intrusion are combatted by increasing groundwater recharge through the construction of water traps and drainage reservoirs and increasing vegetation cover (Pramono, 2021). However, if not managed properly MAR can introduce pollutants and pathogens into groundwater resources (e.g., Raicy et al., 2012; Casanova et al., 2016; Alam et al., 2021). For example, a review of studies using stormwater for MAR revealed that dissolved organic carbon, selected metals and *E. coli* are effectively removed from recharge water during the infiltration process, but that trace organics and *Enterococcus* bacteria were still present (Alam et al., 2021).

Policy-driven groundwater demand management has been successful in the drought-prone Central Coast region of California (USA) where groundwater supplies 90% of the drinking water (Langridge and Van Schmidt, 2020). In response to the severe drought of 2012–2016 experienced in the area, a Sustainable Groundwater Management Act (SGMA) was passed to mitigate groundwater storage loss (Langridge and Van Schmidt, 2020). Although the SGMA does not take into account groundwater losses prior to the passing of the Act, mitigation strategies related to groundwater include using flood flows rather than groundwater for MAR and irrigation purposes and developing local groundwater drought reserves to avoid irreversible groundwater losses during drought periods. The latter is achieved through, for example, using agricultural return flow for recharge, of which a portion is then available to farmers for irrigation during droughts (Langridge and Van Schmidt, 2020).

Another example of a coastal urban area that is prone to severe droughts and is predicted to be impacted by increased temperatures and decreases in surface water resources is that of Perth, Australia (population of 1.6 million) (Serrao-Neumann et al., 2017). During the Millennium Drought (1996–2010) in southern Australia, it was proposed that the water supply in Perth be further augmented from the West Yarragadee aquifer, however, desalination of seawater was implemented instead (Lam et al., 2016). During 2013–2014 about 42% of Perth's water supply was from groundwater, while desalination provided 39% of supply. More recently, MAR is also being considered to supplement water supply. Interestingly, the urban water use in Perth remained lower post-drought than that of pre-drought use, despite increased urban population, suggesting the value of social awareness and behavioural shifts in managing water scarcity. However, the energy use of the water supply system has doubled (Lam et al., 2016).

Several other interventions have been successful in decreasing/managing pollution and salinisation risks such as alternating/seasonal pumping regimes, pumping limits and hard-engineering approaches (e.g., subsurface dams, cut-off walls, semi-pervious subsurface barriers; Chang et al., 2019), rehabilitation of dune systems and the removal of alien trees (Giambastiani et al., 2017), and identifying sources of groundwater-borne pollutants (Michael et al., 2017). Some of these interventions are not without adverse effects. For example, sub-surface dams can result in the accumulation of landward pollutants behind the barrier, increase inland soil salinisation and prevent groundwater discharge to the coastal zone (Chang et al., 2019).

Depending on the scale of a drought event, groundwater demand may be effectively managed by a range of options in the short to medium term (Parisi et al., 2018), including alternative sources such as RWH, the recycling of water and desalinisation. RWH is perhaps the most universally applied method (Wurthmann, 2019) and can be used at a household (e.g., tank) or catchment (impoundment or for groundwater recharge) scale. For example, in Bangladesh, rainfall in coastal areas is higher than inland and RWH in urban areas is considered a suitable resource for drinking and residential purposes (Islam et al., 2015). Conversely in Florida USA, RWH used for residential outdoor irrigation could meet more than half the future water demand under a high population growth scenario and may perform better than other alternative sources such as reclaimed water (Wurthmann, 2019). The long-term reliability of RWH is, however, a concern since harvesting units are usually designed for current precipitation patterns and future rainfall variability is imminent due to climate change (Islam et al., 2015). In addition, at a catchment scale RWH through impoundments could reduce streamflow (Glendenning and Vervoort, 2011).

The recycling of storm- and/or wastewater for irrigation purposes (Lavrnić et al., 2017), MAR (Alam et al., 2021 and references therein) and even potable use (Lee and Tan, 2016) is a climate-resilient water source. However, integration into water supply systems is not as readily accepted due to public perceptions as well as contamination and health risks (Gu et al., 2015; Garcia-Cuerva et al., 2016). The use of reclaimed water for irrigation is considered a suitable option since the water already contains nutrients and therefore reduced fertiliser application is required (Lavrnić et al., 2017). Other innovations such as altered agricultural water supply systems (e.g., drip irrigation) or drought-resistant crops will be essential for future agricultural practices (Oude Essink, 2001; Lavrnić et al., 2017). Finally, desalination of brackish and seawater is a viable option for coastal urban water supply but is often expensive, energy-intensive and can have negative impacts on

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coastal biodiversity through brine by-products (Singh et al., 2021 and see below case study).

Other management solutions include aquifer protection, through for example financial incentives to reduce groundwater abstraction and associated negative impacts. For instance, groundwater abstraction tax has been implemented in Jakarta and it was suggested that groundwater abstraction is spatially controlled (e.g., limiting abstraction to volcanic lithologies rather than subsidence-prone sedimentary lithologies) (Taftazani et al., 2022).

Drought management successes have also been achieved through adjusted water tariffs, integrated management of water resources, conservative water-use practices (residents and tourists), as well as the re-definition of management and policy systems (Parisi et al., 2018; Singh et al., 2021 and the references therein). Furthermore, it is crucial that groundwater modelling of water supply systems is included into drought policies and long-term planning. These models must take into account the present status of the aquifer(s) and be informed by baseline monitoring assessments and extraction rate information. However, a lack of monitoring and unmetered groundwater use poses a major challenge for groundwater management modelling (Hunter et al., 2016; Keir et al., 2019; Rochford et al., 2022). Recent innovations in groundwater modelling have meant that hydrological deficits can be distinguished from the effects of over-abstraction and that aquifer responses can be linked to decision-making (Petersen-Perlman et al., 2022). In addition, advances have been made in the understanding of aquifer vulnerability in terms of both volume and quality during droughts related to pumping and pollution. However, the effects of augmentation strategies such as MAR need to be incorporated more sufficiently (Petersen-Perlman et al., 2022). Finally, it is essential that issues related to groundwater use during droughts are effectively communicated and that local stakeholders participate in managing groundwater resources (Petersen-Perlman et al., 2022).

Both land and water management need to be proactive rather than reactive to ensure that coastal groundwater resources are managed adequately for the economy, health and environment (Michael et al., 2017). Integrated coastal groundwater management needs to take into account geological, hydrological and biogeochemical complexity whilst also accounting for human complexity in terms of economic, cultural and decision-making factors (Michael et al., 2017). Thus, environmental and hydrological connections between cities and the surrounding areas, future uncertainties related to water availability, and a holistic landscape view is required in planning (Serrao-Neumann et al., 2017; see Figure 2).

Case study: A comparison of two South African metropolitan municipalities

Several South African urban areas are struggling to meet water supply requirements due to growing demand, decreased rainfall and poor governance (e.g., Olivier and Xu, 2019; Mahlalela et al., 2020; Pamla et al., 2021). Two large, coastal metropolitan municipalities, the City of Cape Town (CoCT) in the Western Cape province and the Nelson Mandela Bay Metropolitan Municipality (NMBM) in the Eastern Cape province (see Figure 3), have faced or are facing "Day Zero" where the water supply systems are expected to fail (e.g., Pamla et al., 2021).

Although all droughts do not necessarily evolve into water crises (Wolski, 2018), both municipalities rely primarily on rain-fed surface water resources (e.g., Luker and Harris, 2019; NMBM, 2022), which makes them vulnerable to reduction in precipitation in the short to medium term (see Table 1). This is especially

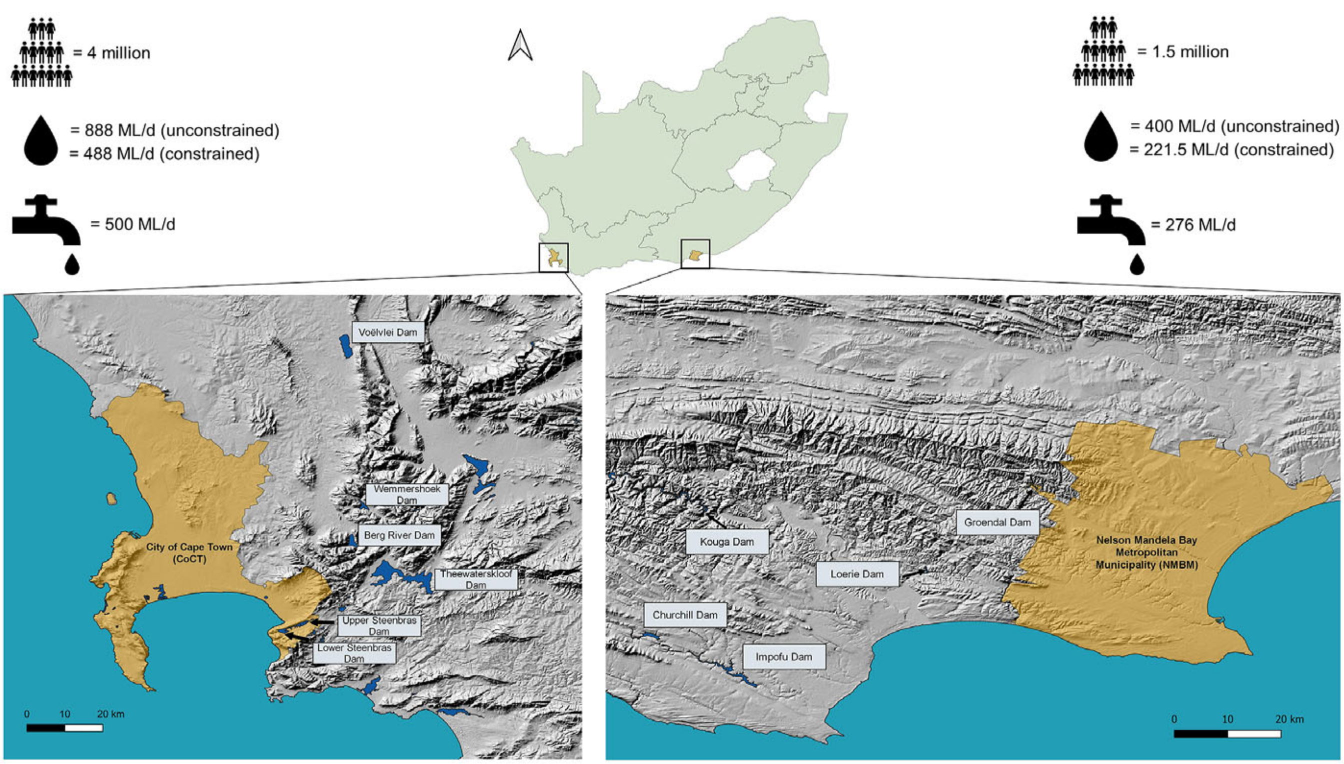

Figure 3. Locations of City of Cape Town and Nelson Mandela Bay Metropolitan Municipalities and their major supply dams. Urban population size, unconstrained and constrained surface water supplies available to the municipalities and water use during the drought are also indicated.

Table 1. Direct comparison of the case-study scenarios which highlight the relevant regional context and management responses to local drought-related water scarcity

	City of Cape Town	Nelson Mandela Bay Metropolitan Municipality
Meteorology	400–2,000 mm MAP; Mediterranean (Ziervogel, 2019)	400–1,500 mm MAP; Temperate (NMBM, 2022)
Urban population size	4 million (Ziervogel, 2019)	1.5 million (NMBM, 2022)
Supply system	Western Cape Water Supply System	Algoa Water Supply System
Surface water reservoir infrastructure	14 dams; 6 main: Theewaterskloof, Voëlvlei, Berg River, Wemmershoek, Upper and Lower Steenbras (Wolski, 2018; Ziervogel, 2019)	9 dams; 5 main: Churchill, Impofu, Kouga, Loerie, Groendal (NMBM, 2022)
Total surface water resource capacity	~900,000 Ml (Ziervogel, 2019)	~286,000 Ml (bulk water storage); 210 Ml/day (Nooitgedagt) (DWS, 2018; NMBM, 2022)
Unconstrained available capacity to municipality	~888 Ml/day (Van Zyl and Jooste, 2022)	400 Ml/day (190 Ml/day bulk water storage; 210 Ml/day Nooitgedagt) (NMBM, 2022)
Constrained available capacity to municipality	~488 Ml/day (Van Zyl and Jooste, 2022)	221.5 Ml/day (NMBM, 2022)
Local aquifers	TMGA, CFA, Atlantis Aquifer (Ziervogel, 2019)	TMGA; Algoa Group Aquifer (Goedhart et al., 2004)
Pre-drought water demand (Feburary–March 2015)	1,200 Ml/day (Enqvist and Ziervogel, 2019)	~315 Ml/day (NMBM, 2022)
Drought water demand	500 Ml/day (Enqvist and Ziervogel, 2019)	276 Ml/day (NMBM, 2022)
Pre-drought groundwater use	1.5% (Luker and Harris, 2019); that is, ~18 Ml/day	5.92 Ml/day (NMBM, 2022)
Groundwater development during drought	20 Ml/day (Atlantis); 10 Ml/day (TMGA); 19 Ml/day (CFA) (Ziervogel, 2019)	Anticipated 41.31 Ml/day (NMBM, 2022)
Desalination	16 Ml/day (CoCT, 2018; Ziervogel, 2019)	Anticipated minimum 15 Ml/day (NMBM, 2022)
Management response to drought	Water restrictions, increased water tariffs, punitive charges, consumer behaviour and public awareness campaign, pressure reduction, flow limiting metres, groundwater development, desalination, water re-use and alien invasive clearing (CoCT, 2018)	Water restrictions, increased water tariffs, punitive charges, consumer behaviour and public awareness campaign, pressure reduction, flow limiting metres, groundwater development, desalination, water re-use, alien invasive clearing, stand pipes and water tanks – informal settlements, leak repairs, upgrade Impofu dam barge, upgrade Linton Grange WTW, Nooitgedagt/Coega Low Level Scheme (NMBM, 2022)

Note: Historical usage of groundwater and potential mitigation and alleviating opportunities provided by groundwater are also given.

pertinent given the coastal setting of these municipalities and the additional climate change challenges that they face (e.g., SLR, coastal flooding and erosion) (e.g., Bornman et al., 2016; Williams and Lück-Vogel, 2020; Dube et al., 2022). Consequently, groundwater reserves are viable alternative freshwater supplies for the metros (e.g., Miller et al., 2017; NMBM, 2022) to mitigate the unsustainable water supply scenario presented by anticipated climate change effects and population growth.

Large-scale, systematic development of groundwater resources for water supply in the CoCT and NMBM was generally limited to times of drought (e.g., 1982–1994 drought in NMBM; Lomberg et al., 1996) or where no other water supply options were available (e.g., rural/small town settings) as groundwater was/is predominantly considered an emergency resource (Cobbing et al., 2015; Luker and Harris, 2019). Furthermore, groundwater resource development for private use was likely driven by socio-economic factors rather than hydrogeological features (Lomberg et al., 1996). This is despite both municipalities having access to suitable aquifers for potential development or water supply diversification (e.g., Pietersen and Parsons, 2002). The recent interest in large-scale abstraction from regional and local aquifers, therefore, provides the municipalities with a comparatively "clean slate" and an opportunity to learn from management successes and failures of other coastal urban areas reliant on groundwater (as discussed above). This case study highlights the groundwater resources available for development in the CoCT and NMBM, municipal groundwater schemes already in place, anticipated/experienced climate change threats and management priorities for sustainable groundwater development in these coastal cities.

For both the CoCT and NMBM an important regional aquifer is that of the Palaeozoic Table Mountain Group aquifer (TMGA), which predominantly consists of quartzitic sandstones that generally yield good quality water (e.g., Rosewarne, 2002; Figure 4). Water is stored in pore space formed by secondary deformation associated with faults, bedding planes and joints (e.g., Pietersen and Parsons, 2002). Shallow, unconfined Cenozoic intergranular aquifers, where water is stored in the primary pore space between interstices of sand grains of fluvial, marine and aeolian deposits, also occur in both municipalities (e.g., Saayman and Adams, 2002; Goedhart et al., 2004; Jovanovic et al., 2017; DWS, 2022). The most important for development being the Atlantis and Cape Flats Aquifers (CFA) for the CoCT (Sandveld Group) (e.g., Enqvist and Ziervogel, 2019; Ziervogel, 2019) and the Algoa Group aquifer for the NMBM (e.g., Goedhart et al., 2004; DWA, 2010; Figure 4).

In NMBM, about 10–15% of supply for the town of Kariega (formerly Uitenhage) is derived from the Uitenhage Springs groundwater (Baron, 2000; DWA, 2010), which equates to about 1.6% of the NMBM water demand (NMBM, 2022). According to the municipal water outlook reports, it is expected that a further 35 Ml of groundwater can be sustainably abstracted per day from

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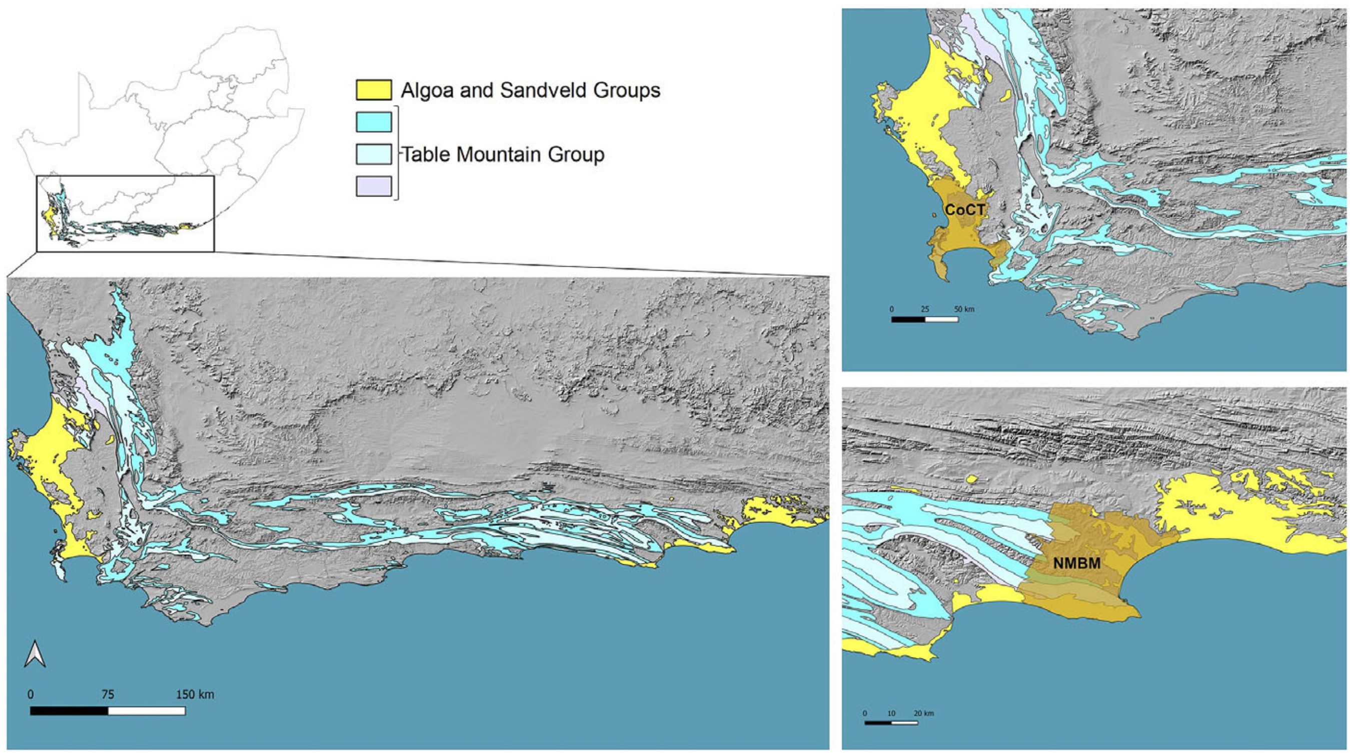

Figure 4. Location and regional extent of the lithological groups of interest for groundwater development in the City of Cape Town (CoCT) and Nelson Mandela Bay Metropolitan (NMBM) municipal areas.

five production well-fields that are being developed in response to the current drought (NMBM, 2022). However, the local NMBM aquifers are poorly understood in terms of inflow sources, recharge, and residence time with scant available hydrogeological literature (e.g., Goedhart et al., 2004; Murray et al., 2008). There is, therefore, a risk that groundwater abstraction during droughts may be a short-term solution should abstraction exceed recharge and aquifer storage. Furthermore, the ecological implications of reduced groundwater discharge (e.g., related to GDEs) are either uncertain or have not been well-considered (e.g., Rishworth et al., 2020b). Pre-drought groundwater use accounted for merely 1.5% of the CoCT water supply and was largely limited to the town of Atlantis (Luker and Harris, 2019). However, groundwater development became an important augmentation strategy during the recent drought for the CoCT, as well as the surrounding agricultural regions, due to the lack of upstream surface water releases and agricultural releases (Watson et al., 2022). Large-scale groundwater projects prompted by the 2015–2018 drought included the proposition to abstract 100 Ml/day from the TMGA and CFA and further MAR schemes in the West Coast area (Luker and Harris, 2019; Zhang et al., 2019b). However, the former was considered unfeasible by experts given the timeline (De Villiers, 2017; Luker and Harris, 2019) with production well-fields still under development years later (Blake et al., 2021; McGibbon et al., 2021) and operational issues due to over-recharge and groundwater flooding were previously encountered with the latter (Zhang et al., 2019b).

South Africa boasts the most reported cases of MAR in Africa of which one of the most notable is the Atlantis scheme (e.g., Dillon et al., 2020; Ebrahim et al., 2020). The scheme has operated since the 1970s (Bugan et al., 2016; LaVanchy et al., 2021) and uses stormwater, domestic and industrial effluent for recharge to meet domestic demand and simultaneously prevent seawater intrusion. Stormwater and treated domestic wastewater are used in the main recharge basins for the former, while industrial wastewater is released into coastal recharge basins for the latter before discharging into the Atlantic Ocean (Bugan et al., 2016). It is estimated that up to 30% of the Atlantis Town water is supplied from the recharge scheme and future expansion has been proposed to increase water resilience (Ebrahim et al., 2020). Although a largely successful example of MAR, groundwater abstraction from the scheme decreased following access to surface water resources and issues related to borehole clogging and turbidity (Bugan et al., 2016). Decreased abstraction and continued MAR resulted in groundwater level increases, which pose threats in terms of groundwater pollution, flooding risks and ecosystem functioning (Bugan et al., 2016; LaVanchy et al., 2021). The management of the scheme has since been improved including actions to prevent iron clogging through ozone injection, monitoring of groundwater levels and quality, and addressing illegal discharges (Bugan et al., 2016). More recently, it has been proposed that MAR is also implemented in the CFA (e.g., Hay et al., 2018; LaVanchy et al., 2021). This would entail that stormwater and domestic wastewater were intercepted before discharging to the ocean. Treated water would be directly injected into the aquifer or recharge could occur through infiltration at wetland areas (Hay et al., 2018). Similarly to the Atlantis scheme, this would increase groundwater storage and a total sustainable yield of 18,000 Ml/a is suggested as feasible (Mauck and Winter, 2021).

Threats of groundwater integration into the water supply systems of the CoCT and NMBM include overexploitation and drawdown. Furthermore, contamination of groundwater resources is a concern (Rosewarne, 2002; Luker and Harris, 2019). For example, seawater intrusion in the coastal suburb of Summerstrand in the NMBM was already reported in the 1990s (Lomberg et al., 1996) and continues to be a concern associated with groundwater use in coastal regions

(Rosewarne, 2002). Developed coastal areas and estuaries within the CoCT and NMBM are also amongst the most threatened areas in South Africa in terms of SLR and the anticipated increase in storm surges (e.g., Theron and Rossouw, 2008; Bornman et al., 2016; Raw et al., 2021; Allison et al., 2022). Resultant saltwater intrusion into estuaries is expected to be amplified by decreased freshwater inflows and altered sediment sources (e.g., Bornman et al., 2016) and aquifer salinisation and higher groundwater levels are expected (Williams and Lück-Vogel, 2020). Coastal flooding has also increased in the CoCT region and is driven by high-intensity rainfall events and larger tidal amplitudes (Dube et al., 2022). Already certain suburbs (e.g., Strand) are subject to frequent coastal flooding and erosion (Williams and Lück-Vogel, 2020) and SLR has caused significant economic losses and damage to infrastructure, threatening tourism activities and World Heritage sites (e.g., Robben Island) (Dube et al., 2021), while dune erosion leaves coastal aquifers vulnerable to seawater intrusion (LaVanchy et al., 2021).

In addition, biofouling and iron-related clogging of boreholes may occur (e.g., Maclear, 2001; Fortuin et al., 2004; Luker and Harris, 2019). Geogenic contamination of the TMGA by high concentrations of radionuclides and metals is a further concern (Mohuba et al., 2022). Other issues include a lack of institutional knowledge, the human capacity for maintenance and monitoring, and the absence of regulatory requirements and implementation of restrictions for domestic groundwater use in South Africa (e.g., Wright and Jacobs, 2016; Luker and Harris, 2019).

Given the coastal setting of the CoCT and NMBM, it is worth noting that desalination of seawater has been proposed as a potential long-term water supply augmentation strategy for both municipalities that is resilient in terms of climate change (Blersch and Du Plessis, 2017; NMBM, 2022). For example, this has been employed as a drought management option at another coastal South African town, Mossel Bay (Sorensen, 2017). However, desalination is an expensive, energy-intensive option with a high carbon footprint compared to other more conventional sources (Gobin et al., 2019). The high electricity costs and frequent electricity outages ("loadshedding") in South Africa is problematic for both desalination as well as groundwater abstraction and pumping, although this may be mitigated through renewable energy supply in the future (Sorensen, 2017; Hattingh, 2022).

From a demand management perspective, both the CoCT and NMBM effectively used several measures to curb water use/loss from the surface water supply systems. These measures included water restrictions, stepped water tariffs, water metres and fixing of water leaks, to mention a few (e.g., Enqvist and Ziervogel, 2019; Ziervogel, 2019; NMBM, 2022). However, mismanagement of water supply systems, ageing infrastructure and maintenance issues contributed to the water crises. For instance, alien invasive vegetation significantly reduces surface runoff and although clearing programmes (viz. Working for Water) exist and is listed as a demand management strategy (NMBM, 2022), it is essential that routine follow-up clearing is conducted in catchments (Enqvist and Ziervogel, 2019; Ziervogel, 2019; Holden et al., 2022). Clearing invasives from dune systems may also have a positive impact on shallow unconfined aquifers, as indicated elsewhere along the coast (Görgens and van Wilgen, 2004). Of concern is that in contrast to surface water resources, systematic management of groundwater resources, restriction of use at a municipal level and detailed information on private groundwater use is lacking (Ziervogel, 2019). For example, the number of registered private boreholes in the CoCT increased from 1,500 to 23,000 within the calendar year of 2017 (Visser, 2018).

Therefore, sustainable groundwater abstraction in the CoCT and NMBM requires comprehensive groundwater monitoring, especially related to baseline datasets for future groundwater scheme locations, and offers the opportunity for knowledge building and the advancement of groundwater management institutions (Luker and Harris, 2019). Routine long-term monitoring of groundwater resources and GDEs is a crucial management priority. The removal of alien vegetation from catchments and dune systems is likely to be beneficial for both surface- and groundwater resources. Furthermore, previous economic valuations of water remediation programs in the case study areas (e.g., Hosking and Du Preez, 2002) should be updated and included in a comprehensive cost–benefit analysis of the development of groundwater monitoring programs for the CoCT and NMBM water supply systems. Finally, sustainable groundwater use may be achieved by the conjunctive use of groundwater resources. This is especially needed during supply deficiencies, surface water infrastructure failures (e.g., blocked/damaged pipes) and contamination issues (Luker and Harris, 2019), such as experienced in the Voëlvlei Dam, CoCT (Luker and Harris, 2019) and in the NMBM (Capa, 2022).

Strategies and solutions linked to managing hydrological variability relevant to metropolitan cities on dynamic coastlines could include inland MAR schemes that effectively would then allow for higher dependency on accessible groundwater aquifers at the coast while minimising risks of saltwater intrusion and groundwater submergence or land subsidence (Dillon et al., 2020; Alam et al., 2021; Pramono, 2021). An urgent research priority should be directed towards quantifying the inland point sources of groundwater recharge, both spatially and volumetrically (e.g., Hall et al., 2020), as well as through legislative policies regulating and monitoring the quantities of residential groundwater abstraction (e.g., Langridge and Van Schmidt, 2020) – one cannot manage what one does not measure. Such research is now underway regionally in South Africa. Knowledge of source-to-sink hydrological connectivity of coastal groundwater cycles would allow interventions to be more effectively directed, such as the removal of water-intensive alien invasive plants in the areas that most directly recharge coastal groundwater-fed aquifers to both improve coastal supply and quality.

Concluding remarks

Coastal aquifers are under increasing pressure due to a myriad of threats affecting the quality and quantity of fresh groundwater resources, often associated with anthropogenic drivers and magnified by climate change and climate extremes. In addition to the "standard" climate change driven impacts, hazards specific to coastal aquifers include SLR, storm surges, seawater intrusion, coastal flooding and erosion. Furthermore, although not unique to coastal aquifers, pressures may be aggravated in coastal areas such as land subsidence due to the unconsolidated nature of sediment and pollution risks since coasts are a nexus for inland and marine contaminants.

Remediation of over-abstracted and contaminated groundwater resources is difficult, costly and in some cases irreversible. Proactive protection of aquifers is therefore crucial for sustainable management of urban water supply. These issues are arguably compounded in coastal cities because of increased water demand due to rapid population growth and urbanisation coupled with decreased recharge. On the other hand, several management solutions and strategies, such as MAR and desalination are practical and potentially the most cost-effective in coastal settings.

To emphasise the issues and management imperatives related to coastal urban water supply and the mitigating role of groundwater during drought-related crises, the investigation of the water supply systems of two South African metropolitan municipalities provides examples of large cities (population > 1 million) experiencing water crises due to anthropogenic (e.g., urbanisation, socio-economic development) and environmental (e.g., decreased precipitation and runoff, increased evapotranspiration) pressures. We specifically chose to highlight this scenario given the regional climate-related future predictions related to increased drought severity. Furthermore, these coastal municipalities rely primarily on surface water resources and therefore have the opportunity to develop integrated water resource management through incorporating alternative water sources, including easily accessible groundwater, into water supply systems. However, the unique coastal pressures facing these groundwater aquifers (e.g., saltwater intrusion and reduced recharge to GDEs) necessitate unique solutions and strategies. Both municipalities implemented several interventions to decrease water demand and increase water supply and although several of these were effective to postpone "Day Zero," it may not be enough to prevent water supply failure in the future.

Future research priorities related to groundwater at the coast need to account for the following most especially: (1) updating and implementing existing policies to develop integrated groundwater management; (2) long-term groundwater monitoring in terms of quantity and quality for both urban and natural systems, especially related to salinity effects and (3) communication of issues, such as land subsidence, seawater intrusion and coastal ecosystem degradation through, for example, decreased discharge related to large-scale groundwater use during droughts, to seek a balance between human-driven water needs and the sustainability of coastal aquifers both in terms of supply quantity and quality.

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References

Abidin HZ, Andreas H, Gumilar I, Sidiq TP and Gamal M (2015) Environmental impacts of land subsidence in urban areas of Indonesia. In *FIG Working Week, 17–21 May. From the Wisdom of the Ages to the Challenges of the Modern World*. Sofia, Bulgaria: International Federation of Surveyors (FIG), pp. 1–12.

Alam S, Borthakur A, Ravi S, Gebremichael M and Mohanty SK (2021) Managed aquifer recharge implementation criteria to achieve water sustainability. *Science of the Total Environment* **768**, 144992.

Allison LC, Palmer MD and Haigh ID (2022) Projections of 21st century sea level rise for the coast of South Africa. *Environmental Research Communications* **4**, 25001.

Bachtouli S and Comte J-C (2019) Regional-scale analysis of the effect of managed aquifer recharge on saltwater intrusion in irrigated coastal aquifers: Long-term groundwater observations and model simulations in NE Tunisia. *Journal of Coastal Research* **35**, 91–109.

Baharuddin M, Masirin M, Hazreek Z, Azman M and Madun A (2018) Resistivity-chemistry integrated approaches for investigating groundwater salinity of water supply and agricultural activity at Island Coastal Area. *Journal of Physics: Conference Series* **995**, 1–10.

Barbier EB (2015) Climate change impacts on rural poverty in low-elevation coastal zones. *Estuarine, Coastal and Shelf Science* **165**, A1–A13.

Baron J (2000) *Groundwater Management using a GIS Case Study: Uitenhage Subterranean Government Water Control Area.* MSc unpublished, University of Cape Town, 1–63 pp.

Befus KM, Barnard PL, Hoover DJ, Hart JAF and Voss CI (2020) Increasing threat of coastal groundwater hazards from sea-level rise in California. *Nature Climate Change* **10**, 946–952.

Bekesi G, McGuire M and Moiler D (2009) Groundwater allocation using a groundwater level response managment method - Gnangara groundwater system, Western Australia. *Water Resources Management* **23**, 1665–1683.

Blake D, Hartnady C, Hay R and Riemann K (2021) Geoethics of bulk groundwater abstraction in an ecologically sensitive area: Steenbras Wellfield (Cape Town). In Abrunhosa M, Chambel A, Peppoloni S and Chaminé HI (eds.), *Advances in Geoethics and Groundwater Management: Theory and Practice for a Sustainable Development*. Cham: Springer Nature, pp. 429–432.

Blersch CL and Du Plessis JA (2017) Planning for desalination in the context of the Western Cape water supply system. *Journal of the South African Institution of Civil Engineering* **59**, 11–21.

Boretti A and Rosa L (2019) Reassessing the projections of the World Water Development Report. *NPJ Clean Water* **2**, 1–6.

Bornman TG, Schmidt J, Adams JB, Mfikili AN, Farre RE and Smit AJ (2016) Relative sea-level rise and the potential for subsidence of the Swartkops Estuary intertidal salt marshes, South Africa. *South African Journal of Botany* **107**, 91–100.

Bugan RDH, Jovanovic N, Israel S, Tredoux G, Genthe B, Steyn M, Allpass D, Bishop R and Marinus V (2016) Four decades of water recycling in Atlantis (Western Cape, South Africa): Past, present and future. *Water SA* **42**, 577–594.

Burri NM, Weatherl R, Moeck C and Schirmer M (2019) A review of threats to groundwater quality in the anthropocene. *Science of the Total Environment* **684**, 136–154.

Cahyadi A (2018) Groundwater quality analysis in dry seasons in Panggang Cay, Kepulauan Seribu, Jakarta, Indonesia. In *IOP Conference Sries: Earth and Environmental Science*. Bristol: IOP, pp. 1–9.

Capa S (2022) *Nelson Mandela Bay' s Water Was Unsafe for Months*. Gqberha: HeraldLive.

Carrión P, Herrera G, Briones J, Sánchez C and Limón J (2018) Practical adaptations of ancestral knowledge for groundwater artificial recharge management of Manglaralto coastal aquifer, Ecuador. *WIT Transactions on Ecology and the Environment* **217**, 375–386.

Casanova J, Devau N and Pettenati M (2016) Managed aquifer recharge: An overview of issues and options. In Jakeman AJ, Barreteau O, Hunt RJ, Rinaudo J-D and Ross A (eds.), *Integrated Groundwater Management*. Zug: Springer, pp. 413–434.

Chang Q, Zheng T, Zheng X, Zhang B, Sun Q and Walther M (2019) Effect of subsurface dams on saltwater intrusion and fresh groundwater discharge. *Journal of Hydrology* **576**, 508–519.

Chesnaux R, Marion D, Boumaiza L, Richard S and Walter J (2021) An analytical methodology to estimate the changes in fresh groundwater resources with sea-level rise and coastal erosion in strip-island unconfined aquifers: Illustration with Savary Island, Canada. *Hydrogeology Journal* **29**, 1355–1364.

Cobbing J (2020) Groundwater and the discourse of shortage in Sub-Saharan Africa. *Hydrogeology Journal* **28**, 1143–1154.

Cobbing JE, **Eales K**, **Gibson J**, **Lenkoe K and Cobbing BL** (2015) Operation and maintenance (O&M) and the perceived unreliability of domestic groundwater supplies in South Africa. *South African Journal of Geology* **118**, 17–32.

CoCT (2018) *Water Outlook 2018 Report Revision 30. Department of Water and Sanitation*. City of Cape Town, South Africa.

Cui D, **Li X and Quinete N** (2020) Occurrence, fate, sources and toxicity of PFAS: What we know so far in Florida and major gaps. *Trends in Analytical Chemistry* **130**, 115976.

De Graaf IEM, **Gleeson T**, **(Rens) Van Beek LPH**, **Sutanudjaja EH and Bierkens MFP** (2019) Environmental flow limits to global groundwater pumping. *Nature* **574**, 90–94.

De Villiers J (2017) Cape Town' s Groundwater Plan Targets 'Impossible'. *News24,* Cape Town, South Africa.

Dillon P, **Escalante EF**, **Megdal SB and Massmann G** (2020) Managed aquifer recharge for water resilience. *Water* **12**, 1–11.

Dube K, **Nhamo G and Chikodzi D** (2021) Rising sea level and its implications on coastal tourism development in Cape Town, South Africa. *Journal of Outdoor Recreation and Tourism* **33**, 100346.

Dube K, **Nhamo G and Chikodzi D** (2022) Flooding trends and their impacts on coastal communities of Western Cape Province, South Africa. *GeoJournal* **87**, S453–S468.

DWA (2010) *Eastern Cape Groundwater Plan*. Port Elizabeth: Department of Water Affairs, Eastern Cape Office, pp. 1–41.

DWS (2018) *Water Reconciliation Strategy Study for the Algoa Water Supply Area. Algoa Reconciliation Strategy Status Report 5*. Reference No. 112546. Department of Water and Sanitation. Pretoria, South Africa.

DWS (2022) *Determination of Water Resource Classes, Reserve and the Resource Quality Objectives in the Keiskamma and Fish to Tsitsikamma Catchments: Water Resources Information, Gap Analyis and Models Report*. Report No. WEM/WMA7/00/CON/RDM/0222. Pretoria: Department of Water and Sanitation.

Ebrahim GY, **Lautze JF and Villholth KG** (2020) Managed aquifer recharge in Africa: Taking stock and looking forward. *Water* **12**, 1844.

Elsayed SM, **Oumeraci H and Goseberg N** (2018) Erosion and breaching of coastal barriers in a changing climate: Associated processes and implication for contamination of coastal aquifers. In *The 36th International Conference on Coastal Engineering (ICCE)*. Baltimore, MD: ICCE, pp. 1–22.

Enqvist JP and Ziervogel G (2019) Water governance and justice in Cape Town: An overview. *WIREs Water* **6**, 1–15.

Erostate M, **Huneau F**, **Garel E**, **Ghiotti S**, **Vystavna Y**, **Garrido M and Pasqualini V** (2020) Groundwater dependent ecosystems in coastal Mediterranean regions: Characterization, challenges and management for their protection. *Water Research* **172**, 115461.

Famiglietti JS and Ferguson G (2021) The hidden crisis beneath our feet. *Science* **372**, 344–345.

Ferguson G and Gleeson T (2012) Vulnerability of coastal aquifers to groundwater use and climate change. *Nature Climate Change* **2**, 342–345.

Flick RE, **Chadwick B and Harper K** (2012) "Flooding" versus "inundation". *Eos, Transactions, American Geophysical Union* **93**, 365–366.

Forbes M and Vogwill R (2016) Hydrological change at Lake Clifton, Western Australia – Evidence from hydrographic time series and isotopic data. *Journal of the Royal Society of Western Australia* **99**, 47–60.

Fortuin M, **Woodford AC**, **Rosewarne PN and Low AB** (2004) *Identification and Prioritisation of Type Areas for Detailed Research in Terms of the Regional Variability of the Groundwater and Ecological Characteristics of the Table Mountain Group Aquifer Systems*. Water Research Commission Report No. 1332/1/04. Pretoria: Water Research Commission, pp. 1–110.

Frommen T, **Groeschke M**, **Nölscher M**, **Koeniger P and Schneider M** (2021) Anthropogenic and geogenic influences on peri-urban aquifers in semi-arid regions: Insights from a case study in northeast Jaipur, Rajasthan, India. *Hydrogeology Journal* **29**, 1261–1278.

Garcia-Cuerva L, **Berglund EZ and Binder AR** (2016) Public perceptions of water shortages, conservation behaviors, and support for water reuse in the U.S. *Resources, Conservation and Recycling* **113**, 106–115.

Garrick DE, **Hall JW**, **Dobson A**, **Damania R**, **Grafton RQ**, **Hope R**, **Hepburn C**, **Bark R**, **Boltz FK**, **De Stefano L**, **O'Donnell E**, **Matthews N and Money A** (2017) Valuing water for sustainable development. *Science* **358**, 1003–1005.

Giambastiani BMS, **Colombani N**, **Greggio N**, **Antonellini M and Mastrocicco M** (2017) Coastal aquifer response to extreme storm events in Emilia-Romagna, Italy. *Hydrological Processes* **31**, 1613–1621.

Gleeson DB, **Wacey D**, **Waite I**, **O'Donnell AG and Kilburn MR** (2016) Biodiversity of living, non-marine, Thrombolites of Lake Clifton, Western Australia. *Geomicrobiology Journal* **33**, 850–859.

Glendenning CJ and Vervoort RW (2011) Hydrological impacts of rainwater harvesting (RWH) in a case study catchment: The Arvari River, Rajasthan, India. Part 2. Catchment-scale impacts. *Agricultural Water Management* **98**, 715–730.

Gobin A, **Sparks D**, **Okedi J**, **Armitage N and Ahjum F** (2019) Assessing the energy and carbon footprints of exploiting and treating brackish groundwater in cape town. *Water SA* **45**, 63–74.

Goedhart M, **Small G and Hulley V** (2004) *Groundwater Targeting in the Algoa Bay Region, from Humansdorp to Alexandria, Eastern Cape, South Africa*. CGS Report No. 2004-0161. Pretoria: Council for Geoscience.

Görgens AHM and Van Wilgen BW (2004) Invasive alien plants and water resources in South Africa: Current understanding, predictive ability and research challenges. *South African Journal of Science* **100**, 27–33.

Gu Q, **Chen Y**, **Pody R**, **Cheng R**, **Zheng X and Zhang Z** (2015) Public perception and acceptability toward reclaimed water in Tianjin. *Resources, Conservation and Recycling* **104**, 291–299.

Habel S, **Fletcher CH**, **Anderson TR and Thompson PR** (2020) Sea-level rise induced multi-mechanism flooding and contribution to urban infrastructure failure. *Scientific Reports* **10**, 1–12.

Hall B, **Currell M and Webb J** (2020) Using multiple lines of evidence to map groundwater recharge in a rapidly urbanising catchment: Implications for future land and water management. *Journal of Hydrology* **580**, 124265.

Han D and Currell MJ (2022) Review of drivers and threats to coastal groundwater quality in China. *Science of the Total Environment* **806**, 150913.

Han D, **Currell MJ**, **Cao G and Hall B** (2017) Alterations to groundwater recharge due to anthropogenic landscape change. *Journal of Hydrology* **554**, 545–557.

Hattingh M (2022) *Keeping the Sprinklers on – Farmers Turning to Wind, Solar to Water Thirsty Crops*. Pretoria: The Water Wheel, pp. 20–23.

Hay R, **Holmes J**, **Atkins JF**, **Coetzee A**, **Hugman R**, **Flügel T**, **Snyman A and De Jager R** (2018) Opportunity in crisis: An interdisciplinary, 'learn by doing' approach to resource management of the cape flats aquifer. In *83rd IMESA Conference*. Port Elizabeth: Institute of Municipal Engineering of Southern Africa, pp. 111–115.

Hepburn E, **Madden C**, **Szabo D**, **Coggan TL**, **Clarke B and Currell M** (2019) Contamination of groundwater with per- and polyfluoroalkyl substances (PFAS) from legacy landfills in an urban re-development precinct. *Environmental Pollution* **248**, 101–113.

Holden PB, **Rebelo AJ**, **Wolski P**, **Odoulami RC**, **Lawal KA**, **Kimutai J**, **Nkemelang T and New MG** (2022) Nature-based solutions in mountain catchments reduce impact of anthropogenic climate change on drought streamflow. *Communications Earth & Environment* **3**, 1–12.

Hosking SG and Du Preez M (2002) Valuing water gains in the Eastern Cape's Working for Water Programme. *Water SA* **28**, 23–28.

Huang Y and Jin P (2018) Impact of human interventions on coastal and marine geological hazards: A review. *Bulletin of Engineering Geology and Environment* **77**, 1081–1090.

Hunter J, **Brooking C**, **Reading L and Vink S** (2016) A web-based system enabling the integration, analysis, and 3D sub-surface visualization of groundwater monitoring data and geological models. *International Journal of Digital Earth* **9**, 197–214.

Hzami A, **Heggy E**, **Amrouni O**, **Mahé G**, **Maanan M and Abdeljaouad S** (2021) Alarming coastal vulnerability of the deltaic and sandy beaches of North Africa. *Scientific Reports* **11**, 1–15.

Islam M, **Afrin S**, **Redwan AM and Rahman M** (2015) Impact of climate change on reliability of rainwater harvesting system: A case study in Mongla, Bangladesh. In *Proceedings of 10th Global Engineering, Science and Technology Conference*. Dhaka, Bangladesh: BIAM Foundation, pp. 220–230.

Jasechko S and Perrone D (2021) Global groundwater wells at risk of running dry. *Science* **372**, 418–421.

Jovanovic N, **Bugan RDH**, **Tredoux G**, **Israel S**, **Bishop R and Marinus V** (2017) Hydrogeological modelling of the Atlantis aquifer for management support to the Atlantis Water Supply Scheme. *Water SA* **43**, 122–138.

Kazakis N (2018) Delineation of suitable zones for the application of Managed Aquifer Recharge (MAR) in coastal aquifers using quantitative parameters and the analytical hierarchy process. *Water* **10**, 1–22.

Keir G, **Bulovic N and McIntyre N** (2019) Stochastic modeling of groundwater extractions over a data-sparse region of Australia. *Groundwater* **57**, 97–109.

Kent CR, **Pandey S**, **Turner N**, **Dickinson CG and Jamieson M** (2020) Estimating current and historical groundwater abstraction from the Great Artesian Basin and other regional-scale aquifers in Queensland, Australia. *Hydrogeology Journal* **28**, 393–412.

Kopsiaftis G, **Tigkas D**, **Christelis V and Vangelis H** (2017) Assessment of drought impacts on semi-arid coastal aquifers of the Mediterranean. *Journal of Arid Environments* **137**, 7–15.

Lam KL, **Lant PA**, **O'Brien KR and Kenway SJ** (2016) Comparison of water-energy trajectories of two major regions experiencing water shortage. *Journal of Environmental Management* **181**, 403–412.

Langridge R and Van Schmidt ND (2020) Groundwater and drought resilience in the SGMA era. *Society & Natural Resources* **33**, 1530–1541.

Lapworth DJ, **Nkhuwa DCW**, **Okotto-Okotto J**, **Pedley S**, **Stuart ME**, **Tijani MN and Wright J** (2017) Urban groundwater quality in sub-Saharan Africa: Current status and implications for water security and public health. *Hydrogeology Journal* **25**, 1093–1116.

LaVanchy GT, **Adamson JK and Kerwin MW** (2021) Integrating groundwater for water security in Cape Town, South Africa. In Mukherjee A, Scanlon B, Aureli A, Langan S, Guo H and McKenzie A (eds.), *Global Groundwater: Source, Scarcity, Sustainability, Security and Solutions*. Amsterdam: Elsevier, pp. 439–449.

Lavrnić S, **Zapater-Pereyra M and Mancini ML** (2017) Water scarcity and wastewater reuse standards in Southern Europe: Focus on agriculture. *Water, Air, and Soil Pollution* **228**, 1–12.

Lee H and Tan TP (2016) Singapore's experience with reclaimed water: NEWater. *International Journal of Water Resources Development* **32**, 611–621.

Li C, **Zhang C**, **Gibbes B**, **Wang T and Lockington D** (2022) Coupling effects of tide and salting-out on perfluorooctane sulfonate (PFOS) transport and adsorption in a coastal aquifer. *Advances in Water Resources* **166**, 104240.

Lomberg C, **Rosewarne P**, **Raymer D and Devey D** (1996) *Research into Groundwater Abstraction in the Port Elizabeth Municipal Area*. WRC Report No. 515/1/97. Pretoria: Water Research Commission, pp. 1–109.

Lorenzo-Lacruz J, **Garcia C and Morán-Tejeda E** (2017) Groundwater level responses to precipitation variability in Mediterranean insular aquifers. *Journal of Hydrology* **552**, 516–531.

Luker E and Harris LM (2019) Developing new urban water supplies: Investigating motivations and barriers to groundwater use in Cape Town. *International Journal of Water Resources Development* **35**, 917–937.

Maclear L (2001) The hydrogeology of the Uitenhage Artesian Basin with reference to the Table Mountain Group Aquifer. *Water SA* **27**, 499–506.

Mahlalela P, **Blamey R**, **Hart N and Reason C** (2020) Drought in the Eastern Cape region of South Africa and trends in rainfall characteristics. *Climate Dynamics* **55**, 2743–2759.

Masciopinto C (2013) Management of aquifer recharge in Lebanon by removing seawater intrusion from coastal aquifers. *Journal of Environmental Management* **130**, 306–312.

Mauck B and Winter K (2021) Assessing the potential for managed aquifer recharge (MAR) of the Cape Flats Aquifer. *Water SA* **47**, 505–514.

McGibbon D, **Hugman R**, **Towers L**, **Riemann K**, **Hay R and Hartnady C** (2021) Long-term planning during emergency response - A no regrets approach and long-term vision for the development of the Cape Flats Aquifer (Cape Town). In Abrunhosa M, Chambel A, Peppoloni S and Chaminé HI (eds.), *Advances in Geoethics and Groundwater Management: Theory and PRactice for a Sustainable Development*. Cham: Springer Nature, pp. 433–436.

Michael HA, **Post VEA**, **Wilson AM and Werner AD** (2017) Science, society, and the coastal groundwater squeeze. *Water Resources Research* **53**, 2610–2617.

Miller JA, **Dunford AJ**, **Swana KA**, **Palcsu L**, **Butler M and Clarke CE** (2017) Stable isotope and noble gas constraints on the source and residence time of spring water from the Table Mountain Group Aquifer, Paarl, South Africa and implications for large scale abstraction. *Journal of Hydrology* **551**, 100–115.

Minnig M, **Moeck C**, **Radny D and Schirmer M** (2018) Impact of urbanization on groundwater recharge rates in Dübendorf, Switzerland. *Journal of Hydrology* **563**, 1135–1146.

Mohuba SC, **Abiye TA**, **Demlie MB and Nhleko S** (2022) Natural radioactivity and metal concentration in the Thyspunt area, Eastern Cape Province, South Africa. *Environmental Monitoring and Assessment* **194**, 112.

Murray R, **Goedhart M and Baron J** (2008) *High-Yielding Groundwater Areas around the Nelson Mandela Bay Municipality*. WRC Report No. TT 327/08. Pretoria: Water Research Commission, pp. 1–26.

Neumann B, **Vafeidis AT**, **Zimmermann J and Nicholls RJ** (2015) Future coastal population growth and exposure to sea-level rise and coastal flooding – A global assessment. *PLoS ONE* **10**, e0118571.

NMBM (2022) *Nelson Mandela Bay Municipality Water Outlook Report 2022*. Gqberha: NMBM, pp. 1–29.

Nogueira G, **Stigter TY**, **Zhou Y**, **Mussa F and Juizo D** (2019) Understanding groundwater salinization mechanisms to secure freshwater resources in the water-scarce city of Maputo, Mozambique. *Science of the Total Environment* **661**, 723–736.

Olivier DW and Xu Y (2019) Making effective use of groundwater to avoid another water supply crisis in Cape Town, South Africa. *Hydrogeology Journal* **27**, 823–826.

Oude Essink GHP (2001) Improving fresh groundwater supply - Problems and solutions. *Ocean and Coastal Management* **44**, 429–449.

Pamla A, **Thondhlana G and Ruwanza S** (2021) Persistent droughts and water scarcity: households' perceptions and practices in Makhanda, South Africa. *Land* **10**, 1–13.

Parisi A, **Monno V and Fidelibus MD** (2018) Cascading vulnerability scenarios in the management of groundwater depletion and salinization in semi-arid areas. *International Journal of Disaster Risk Reduction* **30**, 292–305.

Petersen-Perlman JD, **Aguilar-Barajas I and Megdal SB** (2022) Drought and groundwater management: Interconnections, challenges, and policy responses. *Current Opinion in Environmental Science & Health* **28**, 100364.

Pietersen K and Parsons R (2002) *A Synthesis of the Hydrogeology of the Table Mountain Group - Formation of a Research Strategy*. WRC Report No. TT 158/01. Pretoria: Water Research Commission, pp. 1–265.

Pramono I (2021) Nature-based solutions for integrating flood and land subsidence: A case study in Jakarta and Semarang. In *IOP Conference Sries: Earth and Environmental Science*. Bristol: IOP, pp. 1–10.

Preziosi E, **Frollini E**, **Zoppini A**, **Ghergo S**, **Melita M**, **Parrone D**, **Rossi D and Amalfitano S** (2019) Disentangling natural and anthropogenic impacts on groundwater by hydrogeochemical, isotopic and microbiological data: Hints from a municipal solid waste landfill. *Waste Management* **84**, 245–255.

Rahimi R, **Tavakol-Davani H**, **Graves C**, **Gomez A and Valipour MF** (2020) Compound inundation impacts of coastal climate change: Sea-level rise, groundwater rise, and coastal precipitation. *Water* **12**, 1–16.

Raicy MC, **Parimala Renganayaki S**, **Brindha K and Elango L** (2012) Mitigation of seawater intrusion by managed aquifer recharge. In Elango L, Goyal VC and Thomas W (eds.), *Managed Aquifer Recharge: Methods, Hydrogeological Requirements, Pre and Post Treatment Systems*, Saph Pani. Chennai, India. pp. 83–99.

Rakib MA, **Sasaki J**, **Matsuda H**, **Quraishi SB**, **Mahmud M**, **Bodrud-Doza M**, **Atique Ullah AKM**, **Fatema KJ**, **Newaz M and Bhuiyan MAH** (2020) Groundwater salinization and associated co-contamination risk increase severe drinking water vulnerabilities in the southwestern coast of Bangladesh. *Chemosphere* **246**, 125646.

Raw JL, **Adams JB**, **Bornman TG**, **Riddin T and Vanderklift MA** (2021) Vulnerability to sea-level rise and the potential for restoration to enhance blue carbon storage in salt marshes of an urban estuary. *Estuarine, Coastal and Shelf Science* **260**, 107495.

Rishworth GM, **Cawthra HC**, **Dodd C and Perissinotto R** (2020a) Peritidal stromatolites as indicators of stepping-stone freshwater resources on the Palaeo-Agulhas Plain landscape. *Quaternary Science Reviews* **235**, 1–11.

Rishworth GM, **Dodd C**, **Perissinotto R**, **Bornman TG**, **Adams JB**, **Anderson CR**, **Cawthra HC**, **Dorrington RA**, **Du Toit H**, **Edworthy C**, **Gibb RA**, **Human LRDD**, **Isemonger EW**, **Lemley DA**, **Miranda NAF**, **Peer N**,

Raw JL, Smith AM, Steyn P, Strydom NA, Teske PR and Welman S (2020b) Modern supratidal microbialites fed by groundwater: functional drivers, value and trajectories. *Earth-Science Reviews* **210**, 1–24.

Robertson J (2020) Challenges in sustainably managing groundwater in the Australian Great Artesian Basin: lessons from current and historic legislative regimes. *Hydrogeology Journal* **28**, 343–360.

Rochford LM, Ordens CM, Bulovic N and McIntyre N (2022) Voluntary metering of rural groundwater extractions: understanding and resolving the challenges. *Hydrogeology Journal* **20**, 1–16.

Rohde MM, Froend R and Howard J (2017) A global synthesis of managing groundwater dependent ecosystems under sustainable groundwater policy. *Groundwater* **55**, 293–301.

Rosewarne P (2002) Hydrogeological characteristics of the table mountain group aquifers. In Pietersen K and Parsons R (eds.), *A Synthesis of the Hydrogeology of the Table Mountain Group – Formation of a Research Strategy*. WRC Report No. TT 158/01. Pretoria: Water Research Commission, pp. 33–44.

Rosinger A (2021) Human evolution led to an extreme thirst for water. *Scientific American* **325**, 38–43.

Ruyle BJ, Pickard HM, Leblanc DR, Tokranov AK, Thackray CP, Hu XC, Vecitis CD and Sunderland EM (2021) Isolating the AFFF signature in coastal watersheds using oxidizable PFAS precursors and unexplained organofluorine. *Environmental Science & Technology* **55**, 3686–3695.

Saayman IC and Adams S (2002) The use of garden boreholes in Cape Town, South Africa: Lessons learnt from Perth, Western Australia. *Physics and Chemistry of the Earth* **27**, 961–967.

Schreiner-McGraw AP and Ajami H (2021) Delayed response of groundwater to multi-year meteorological droughts in the absence of anthropogenic management. *Journal of Hydrology* **603**, 126917.

Serrao-Neumann S, Renouf M, Kenway SJ and Choy DL (2017) Connecting land-use and water planning: Prospects for an urban water metabolism approach. *Cities* **60**, 13–27.

Shirzaei M, Freymueller J, Törnqvist TE, Galloway DL, Dura T and Minderhoud PSJ (2021) Measuring, modelling and projecting coastal land subsidence. *Nature Reviews Earth & Environment* **2**, 40–58.

Singh C, Jain G, Sukhwani V and Shaw R (2021) Losses and damages associated with slow-onset events: Urban drought and water insecurity in Asia. *Current Opinion in Environmental Sustainability* **50**, 72–86.

Sorensen P (2017) The chronic water shortage in Cape Town and survival strategies. *International Journal of Environmental Studies* **74**, 515–527.

Stigter T, Nunes J, Pisani B, Fakir Y, Hugman R, Li Y, Tomé S, Ribeiro L, Samper J, Oliveira R, Monteiro J, Silva A, Tavares P, Shapouri M, Cancela da Fonseca L and El Himer H (2014) Comparative assessment of climate change and its impacts on three coastal aquifers in the Mediterranean. *Regional Environmental Change* **14**, S41–S56.

Su X, Liu T, Beheshti M and Prigiobbe V (2020) Relationship between infiltration, sewer rehabilitation, and groundwater flooding in coastal urban areas. *Environmental Science and Pollution Research* **27**, 14288–14298.

Sunderland EM, Hu X, Dassuncao C, Tokranov AK, Wagner CC and Allen JG (2019) A review of pathways of human exposure to poly- and perfluoroalkyl substances (PFASs) and present understanding of health effects. *Journal of Exposure Science and Environmental Epidemiology* **29**, 131–147.

Taftazani R, Kazama S and Takizawa S (2022) Spatial analysis of groundwater abstraction and land subsidence for planning the piped water supply in Jakarta, Indonesia. *Water* **14**, 3197.

Theron AK and Rossouw M (2008) Analysis of potential coastal zone climate change impacts and possible response options in the southern African region. In *Proceedings from the Science Real and Relevant: 2nd CSIR Bienniel Conference*. Pretoria: CSIR, p. 1.

Unsal B, Yagbasan O and Yazicigil H (2014) Assessing the impacts of climate change on sustainable management of coastal aquifers. *Environmental Earth Sciences* **72**, 2183–2193.

Van Zyl A, Jooste JL (2022) Retaining and recycling water to address water scarcity in the City of Cape Town. *Development Southern Africa* **39**, 108–125.

Visser WP (2018) A perfect storm: The ramifications of Cape Town's drought crisis. *The Journal for Transdisciplinary Research in Southern Africa* **14**, 1–10.

Vitousek S, Barnard PL and Limber P (2017) Can beaches survive climate change? *Journal of Geophysical Research: Earth Surface* **122**, 1060–1067.

Warden JG, Coshell L, Rosen MR, Breecker DO, Ruthrof KX and Omelon CR (2019) The importance of groundwater flow to the formation of modern thrombolitic microbialites. *Geobio* **17**, 536–550.

Watson A, Miller J, Künne A and Kralisch S (2022) Using soil-moisture drought indices to evaluate key indicators of agricultural drought in semi-arid Mediterranean Southern Africa. *Science of the Total Environment* **812**, 152464.

Williams LL and Lück-Vogel M (2020) Comparative assessment of the GIS based bathtub model and an enhanced bathtub model for coastal inundation. *Journal of Coastal Conservation* **24**, 1–15.

Wolski P (2018) *What Cape Town Learned from its Drought*. Chicago, IL: Bulletin of the Atomic Scientists.

Wright T and Jacobs HE (2016) Potable water use of residential consumers in the Cape Town metropolitan area with access to groundwater as a supplementary household water source. *Water SA* **42**, 144–151.

Wurthmann K (2019) Assessing storage requirements, water and energy savings, and costs associated with a residential rainwater harvesting system deployed across two counties in Southeast Florida. *Journal of Environmental Management* **252**, 109673.

Zhang X, Lohmann R and Sunderland EM (2019a) Poly- and perfluoroalkyl substances in seawater and plankton from the Northwestern Atlantic Margin. *Environmental Science and Technology* **53**, 12348–12356.

Zhang H, Xu Y and Kanyerere T (2019b) A modelling approach to improving water security in a drought-prone area, West Coast, South Africa. *Physics and Chemistry of the Earth* **114**, 102797.

Ziervogel G (2019) *Unpacking the Cape Town Drought: Lessons Learned*. Cape Town: Cities Support Programme and National Treasury of South Africa, pp. 1–29.